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A Comparison of Wind Readings from LIDAR, Hot Wire, and Propeller & Vane Anemometers over Time Periods Relevant to Fire Control Applications

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14. ABSTRACT

The work presented within compares the wind readings obtained from a weapon mountable hot wire anemometer and co-located down range laser wind sensor to the data collected from a string of propeller and vane anemometers set up along a firing line. The purpose of this effort was to determine if a combination of the two sensors would be able to measure the wind conditions a projectile would be subject to along its flight path to a target. The results of the work showed that the sensor suite was only able to partially capture the atmospheric disturbances affecting projectile flight. The hot wire anemometer was able to accurately report the long term trends in the wind as well as the short term deviations at the firing platform. The laser anemometer, however, was only able to capture the long term average winds at several predetermined downrange distances. These results show that further work needs to be conducted to quantify the effect of each type of wind reading on the ballistic solution before evaluating the utility of each sensor in a fire control application.

15. SUBJECT TERMS

Wind Sensor, LIDAR Anemometer, Wind Correction, Ballistic Winds

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Background

It is known that the atmospheric winds between a weapon system and its target can influence the flight path of the projectile to said target and result in a round delivery error. To correct for this, some weapon systems make an adjustment to the pointing angle of the gun tube that compensates for the expected deflection of the round due to wind. However, this functionality is very limited because the corrections are solely based on the wind sampled at the vehicle. Winds, in general, do not remain constant over long distances(1,2) which causes a mismatch between the data a Fire Control System (FCS) uses to calculate a wind correction and the actual wind the projectile is subject to. To get around this difficulty, a LIDAR wind sensor could be used to read the winds ahead of the vehicle and make a more accurate ballistic correction. Unfortunately, this is not a straight forward integration effort as it is unknown whether the winds reported by a LIDAR sensor are representative of the winds that would act upon a projectile. Therefore, this aspect of the potential solution requires further investigation.

What makes this problem unique is that LIDAR wind sensors use a different sample space to read the wind than the traditional cup and ball (CnB) or propeller and vane (PnV) anemometers. The CnB and PnV read the wind at a particular point in space. LIDAR sensors, on the other hand, work by averaging the motion of the air from a sampled volume of the atmosphere. Previous work has shown that there is a good correlation between a LIDAR sensors and one of these traditional sensors (3,4). However, these works used a 10 min running average to show that the long term / steady state winds are similar. This methodology is not applicable in the fire control realm as the LIDAR sensor puts out an active signature which could potentially give away the weapon system's location. Additionally, taking a 10 minute average of the wind before firing a round is not realistic. These restrictions limit the sample time of the wind to a short interval of about 3 seconds, which is how long it takes for a gunner to laze, track, and fire (5,6).

Given that the previous work is not applicable to the problem at hand, one cost effective way to determine the correlation between the projectile winds and LIDAR readings is to use point wind sensors to sample the wind along a projectile's trajectory and compare that data to the LIDAR output. If a good correlation is found between the two data sets, then that would indicate that the LIDAR sensor could be used to improve the wind correction in a FCS.

Purpose

Aberdeen Proving Ground (APG) has been using propeller and vane (PnV) anemometers to measure winds for ballistic applications for some time now. They have a sensor array setup at Barricade 1 that measures the wind speed and direction at various down range distances (range gates). The goal of this experiment was to setup a LIDAR wind sensor at Barricade 1 and measure the winds along the same line of sight (LOS) as the APG anemometers. Then, as described in the background section, use this data to determine if a LIDAR sensor data could be used to improve the ballistic wind correction calculated by a FCS in an engagement scenario.

Experimental Setup:

The experimental equipment consisted of a LIDAR anemometer and a hot wire (HW) anemometer. This particular combination of sensors was used as it representative of the equipment a weapon platform would make use of to address the need for a more accurate wind correction. The hot wire anemometer collected data at the 0m position and the LIDAR anemometer was used to measure winds at the 200m, 300m, 400m, 500m, 600m and 700m positions. The physical setup of the sensors is pictured below in figure 1:

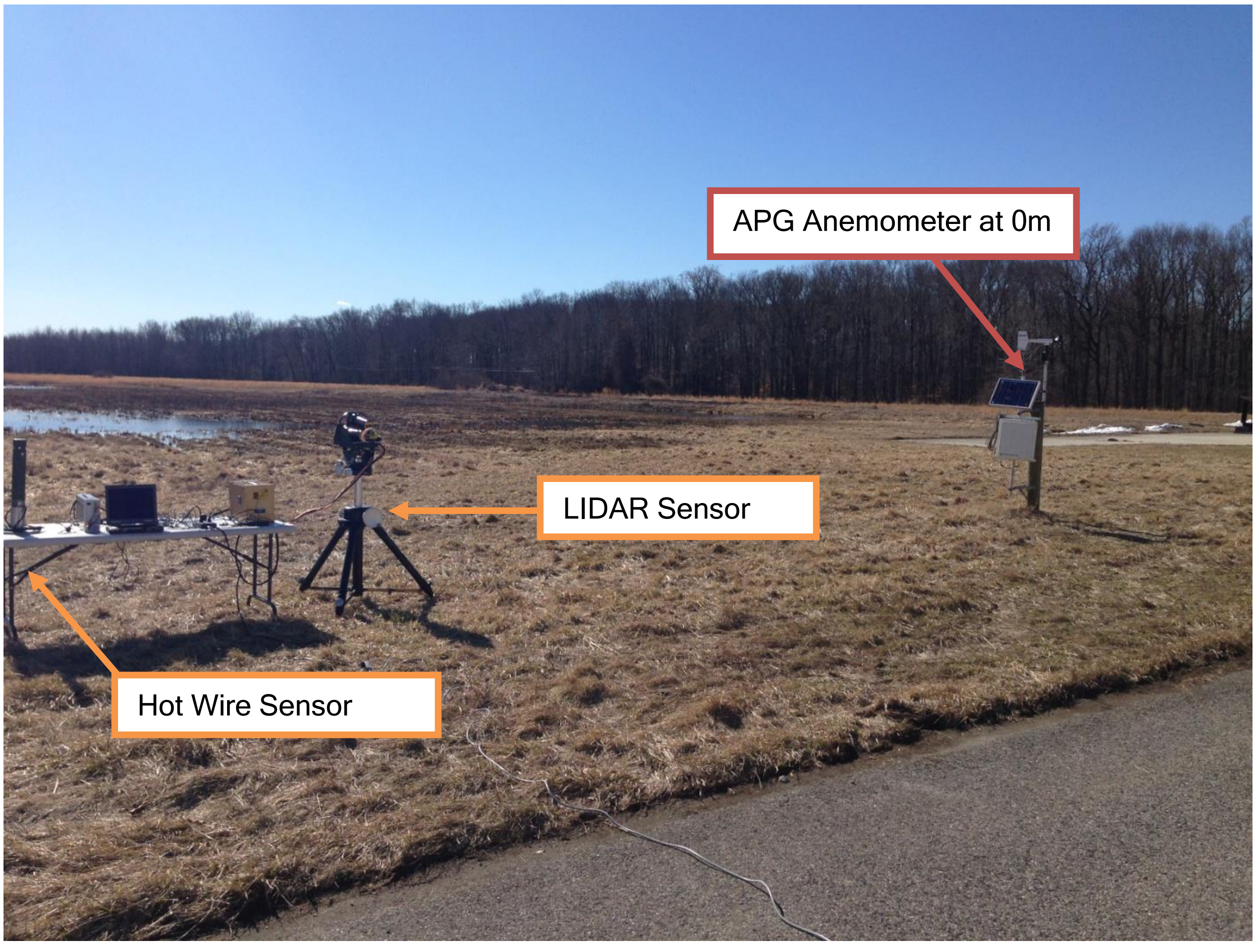

Figure 1: Photograph of Experimental Setup

The experimental sensors were setup at the 0m position and close to the APG sensor to ensure the HW anemometer was sampling similar winds as the PnV anemometer. The LIDAR sensor's LOS was directed down range to match the LOS of the APG sensors.

The APG PnV anemometers were setup at 126m, 376m, 625m down range from the first sensor. A comparison of the LIDAR and APG range gates is pictured below in figure 2:

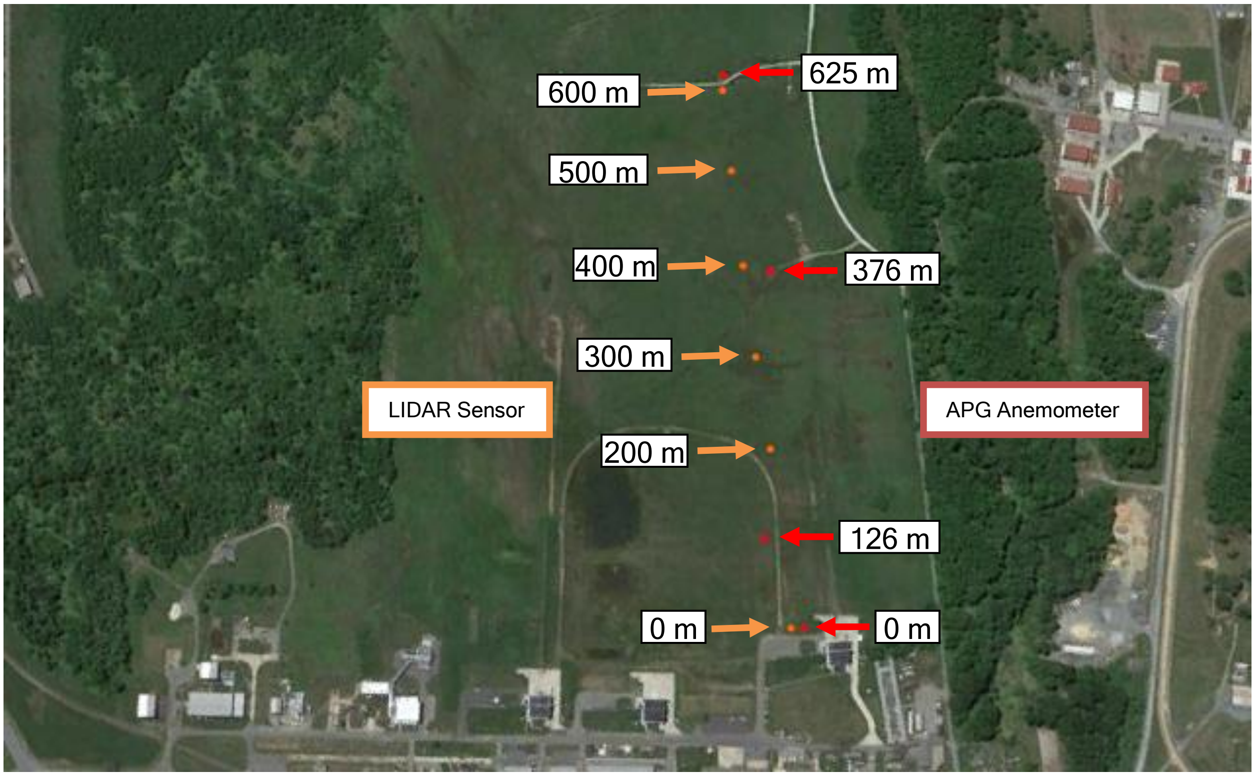

Figure 2: Aerial Map of Range Gates

As Figure 2 shows, the two sensor arrays could not be setup in such a way that every range gate would match. This is due to the different step sizes between the range gates for each sensor array. However, the two sensor suites were close to being lined up at the 0m, 400m, and 600m positions.

In addition to the down range distances, the heights of the APG sensors needed to be considered. The APG sensor height increases with range. To compensate for this, the base lenses on the LIDAR sensor were pitched to match the height of the APG sensors as closely as possible. The optimal pitch was calculated to be 0.6 degrees. However, in order to obtain readings from the required range gates, a pitch of 1.1 degrees was used. The alignment of the of the range gate pitch is pictured below in figure 3:

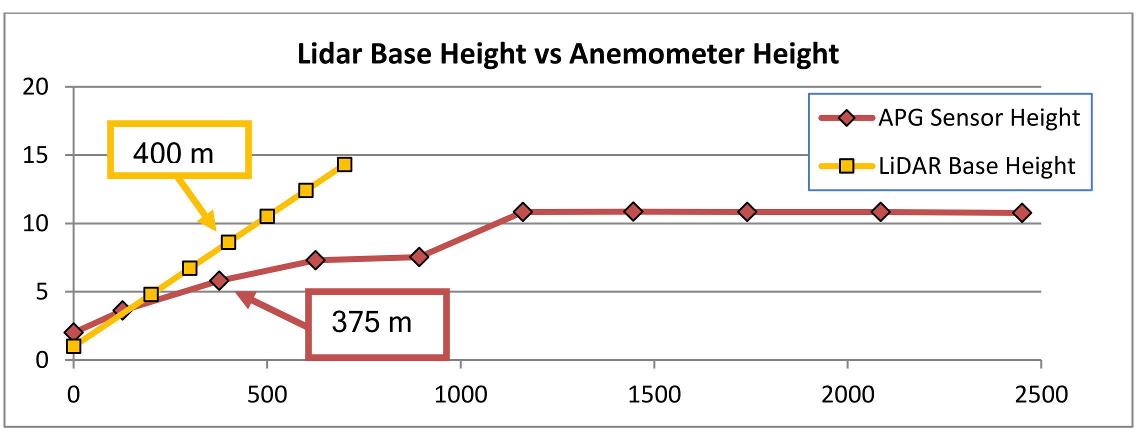

Figure 3: Plot of Range Gate Heights

Figure 3 shows that there was about a 3.5m difference in height between the 400m LIDAR range gate and the 375m APG range gate.

Given the geometry of the problem, the data obtained at the 0m range gate is appropriate for the comparison of the HW anemometer to the APG PnV anemometer and the LIDAR data obtained at the 400m range gate can be compared to the APG PnV anemometer at the 375m range gate. At the 0m mark, the difference in sample space was minimal. At the 375m/400m range gate, the difference in the sample space is represented below in figure 4:

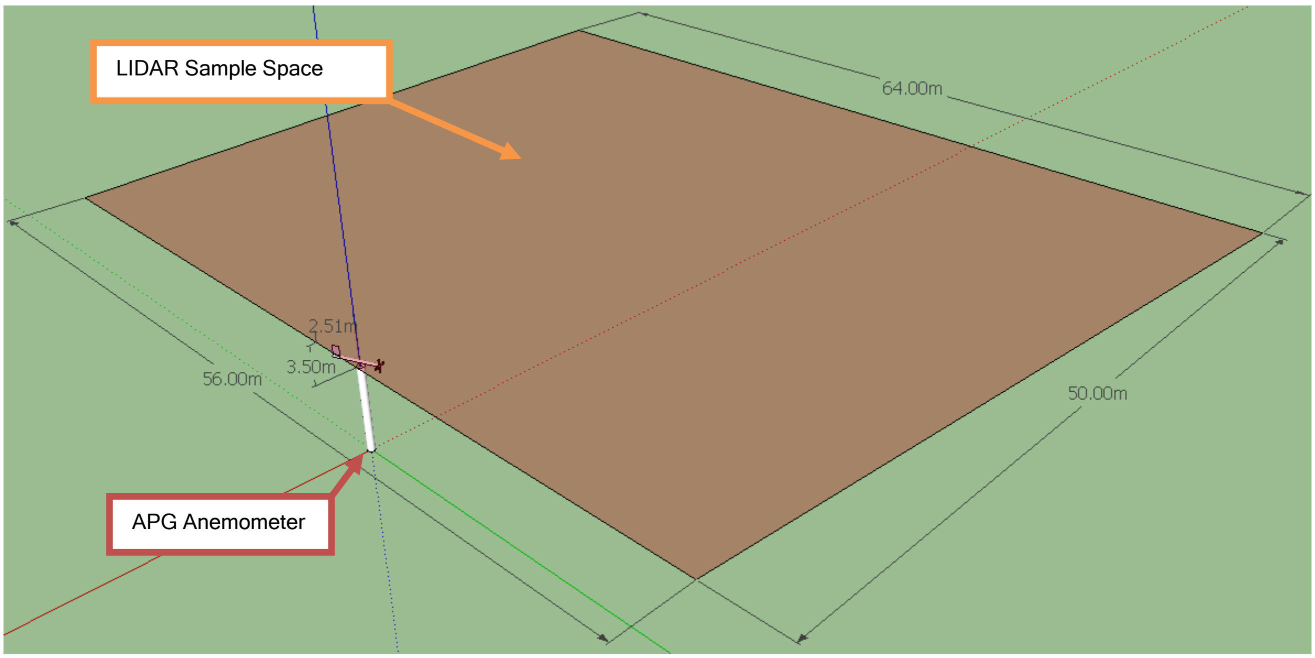

Figure 4: LIDAR Sample Space

Figure 4: LIDAR Sample Space shows that the LIDAR sample space started at the APG anemometer and extended approximately 50m down range. Ideally, the center of the LIDAR sample space should have been lined up with the APG anemometer but the physical limitation of the setup made this impossible. Nevertheless, the sample spaces were close enough that it was worth collecting and comparing wind data to see how the values align.

Data Collection Process

The data collection for this experiment was simple. The experimental sensors were connected to a laptop and logging software captured the values reported by the sensors. The HW anemometer reported the wind speed and direction every 5 sec using a 5 sec running average. The LIDAR sensor reported the wind speed and direction at each range gate every second using a 1 second average. This data set reported the wind speed and direction at each PnV anemometer every second using a 3 second running average.

Data Processing

The objective of the data processing was to trim the data sets, fill in dropped lines, find a sensor orientation correction, and align the time stamps of the data. This was necessary to allow for the direct comparison of individual data points as well as and long term averages.

Each wind sensor reported data to an independent file/location using a unique format. Due to this, the data could not be compared directly as each file represented the wind values differently. To correct this formatting issue, the relevant data was extracted manually, trimmed to only include the data lines with time stamps common to all 3 datasets, and repackaged into a standard format.

Next, each data file was scanned to check for missing data points. Data holes were reported and small gaps were filled using spline interpolation. The data sets did not contain holes larger than 3 rows, so corrupting the results by filling in large sections of missing data was not a concern.

The data sets were then used to find a sensor orientation correction. The experimental sensors could not be aligned precisely to the LOS of the APG sensors as no equipment was available to do this. Therefore, the sensors were visually aligned as accurately as possible. This lack of precision is important because to find the wind effects on a projectile, a vectored wind must be broken down into its Cartesian components relative to the LOS. A misalignment in the 0 direction (north) will translate to an error in the cross wind and range wind components. To address this issue, an iterative search was used to find a best direction offset correction. Previous work showed that if two sensors are aligned correctly, a high correlation coefficient between the components of the winds could be calculated. Therefore, the search picked out the correction that resulted in the highest minimum correlation coefficient between the range wind and cross wind. The corrections for both experimental sensors were small. This makes sense as care was taken to visually align the sensors during the experimental setup.

The above search was run in parallel with a search for a proper time stamp offset. Given that the data was obtained from 3 different devices that could potentially have different values for their internal clocks, there was a high chance that the experimental data needed to be shifted in time in order to align to the truth data properly. The correlation coefficient used in the direction offset search is influenced by the sensor alignment to north as well as the time stamp alignment. Therefore, the searches for the optimal values for these two corrections were performed together. This process resulted in data sets that could be directly compared in subsequent analysis.

Data Analysis

The goal of the data analysis was to determine the correlation between the test and truth sensors and to quantify the magnitude of the error between them. The APG sensors were considered the truth values for the wind because they measured the wind at a specific point in space. If a projectile was fired though a trajectory that matched the placement of the APG sensor, it would be subject to the winds read by that sensor. Therefore, if the experimental sensors have a high degree of correlation to the truth sensor, then that can be interpreted as the experimental sensors reading the same wind that would influence a projectile's flight at that point. This, in turn, means that a ballistic correction based on the experimental sensor data would result in an accurate wind correction.

It was not expected that the experimental sensors will match the truth values exactly and therefore an error term was needed to describe the difference between them. Past work described this error by using the mean and standard deviation of the difference between the sensors. The mean error was used to report any biases between the sensors and the standard deviation measured how much the wind is expected to vary between the two sensors at any point in time. So if the mean error between the experimental and truth sensors is 0 and the standard deviation is 0.18 m/s, that means that there is no bias between the two sensors and the difference in the instant values will be less than 0.18m/s 68% of the time, 0.36m/s 95% of the time, and 0.54m/s 99.7% of the time. From a weapon system analysis perspective, this means that if a wind correction based on the experimental sensor data was calculated and applied, it would account for all the wind acting on the projectile except for the value described by the standard deviation. This value is what would contribute to the round delivery error. Therefore, these error terms can be used to quantify the expected performance of the particular experimental sensor in a fire control application.

One last factor that could determine the correlation between the sensors is the averaging time used to report a wind reading. In this analysis, the data is examined in three different ways. They are:

- 10 minute averages for each sensor
- 1 second averages for each sensor
- 10 minute averages for the experimental sensor vs 1 second average for the truth data.

The 10 minute averages for each sensor will be used to determine if the two sensors being compared are reading the same long term / steady state winds. This essentially removes the noise inherent to short term wind readings and ensures that the long term patterns of the wind match.

The 1 second averages for each sensor are useful for determining if a short term wind sample read by an experimental sensor could be used to compensate for the instant winds experienced by a projectile in flight. This comparison is important as it represents how the experimental sensors would more than likely be used once they are integrated onto a weapon platform.

The last comparison is between the instant winds a projectile would experience and the 10 minute averages from the experimental sensors. This comparison is interesting because the classic approach to pre-emptive wind corrections is to use a long term average and ignore the instant values. This comparison examines the value of this approach.

Results

<u>Experimental Hot Wire Anemometer vs APG Propeller & Vane Anemometer at 0m Range Gate</u>

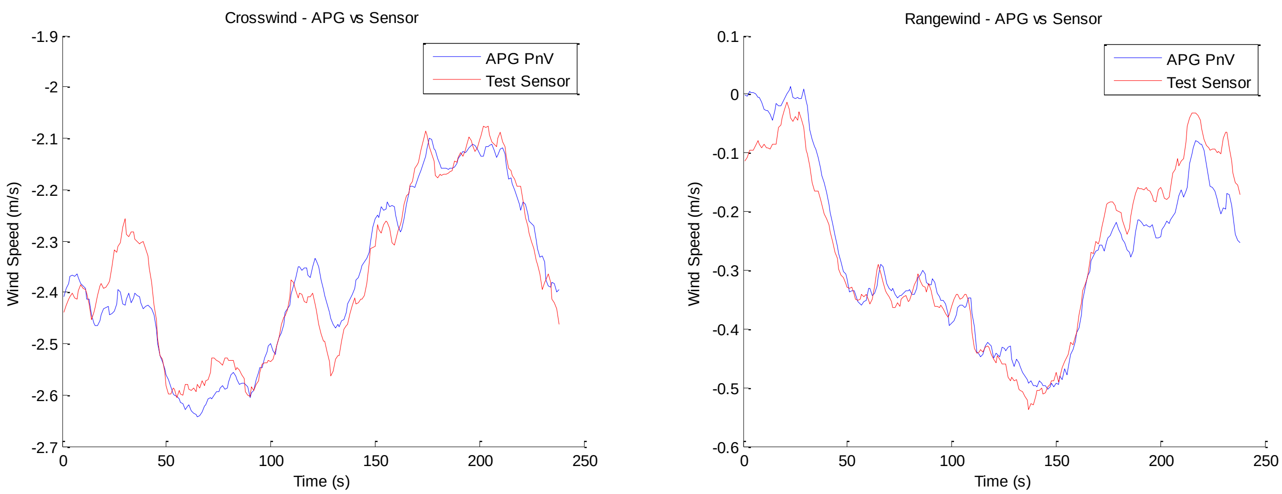

Figure 5: Comparison of the HW Anemometer 10 min Average and PnV Anemometer 10 Minute Average

Figure 5 shows that the two sensors follow the same long term trends and that the difference between the readings is small. This is verified by a correlation coefficient of 0.95, 0 m/s mean error, and a standard deviation of the error of 0.05 m/s. This figure also shows that the data between the two sensors is aligned correctly as the expected high correlation value was achieved.

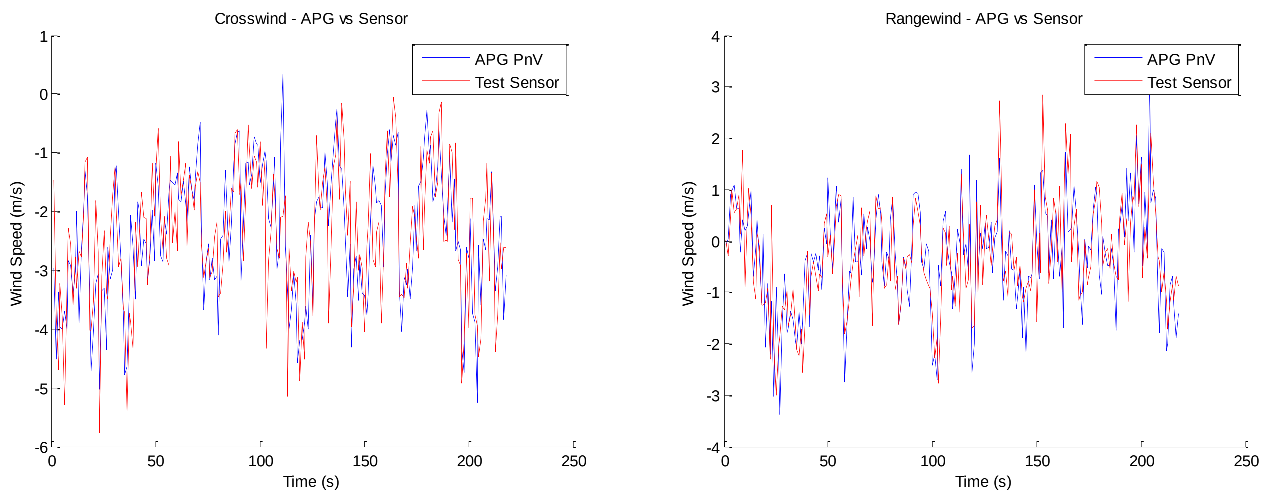

Figure 6: Comparison of the HW Anemometer 1 sec Average and PnV Anemometer 1 sec Average

Figure 6 shows that even the 1 second / instant values from the two sensors match very closely. The correlation coefficient was 0.74, the mean error was 0 m/s, and a standard deviation was 0.85 m/s. While this is worse than the long term averages, it does show that a large portion of the instantaneous wind can be captured by the sensor.

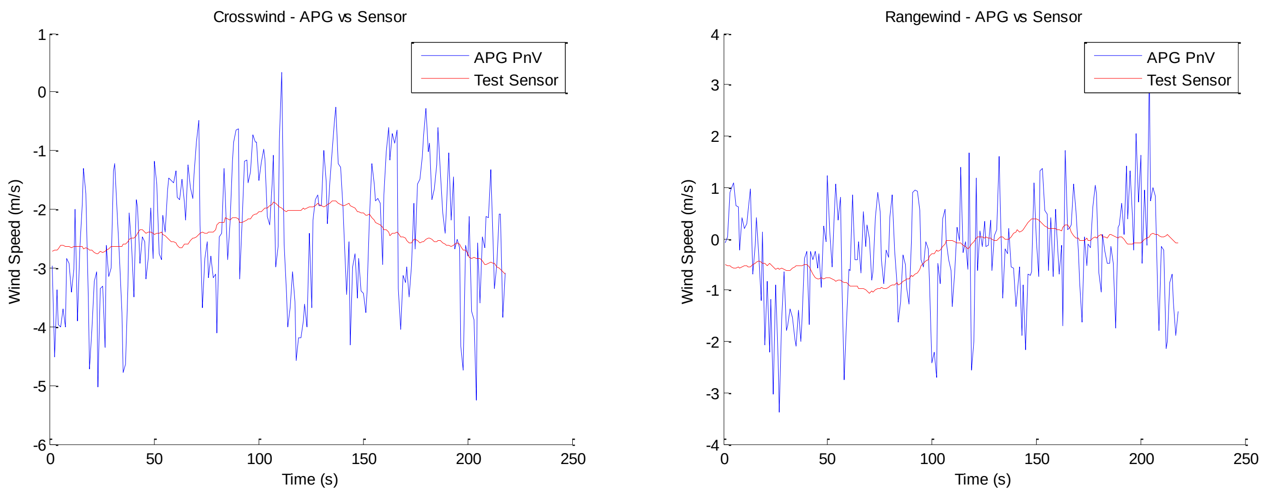

Figure 7: Comparison of the HW Anemometer 10 minute Average and PnV Anemometer 1 sec Average

Figure 7 shows that the 10 minute average captures the mean wind values about which the instant values are scattered. The correlation was 0.09, the mean was 0 m/s, and the standard deviation was 1.09 m/s.

These results show that the HW anemometer does a good job of capturing the winds. Surprisingly, the standard deviation of the error for the instant wind readings was smaller than for the 10 minute average. This shows that the HW anemometer would produce a more accurate wind correction if the fire control system used the instant wind readings from the sensor rather than the 10 minute averages.

LIDAR Anemometer vs Propeller and Vane Anemometer at 400m/375m Range Gate

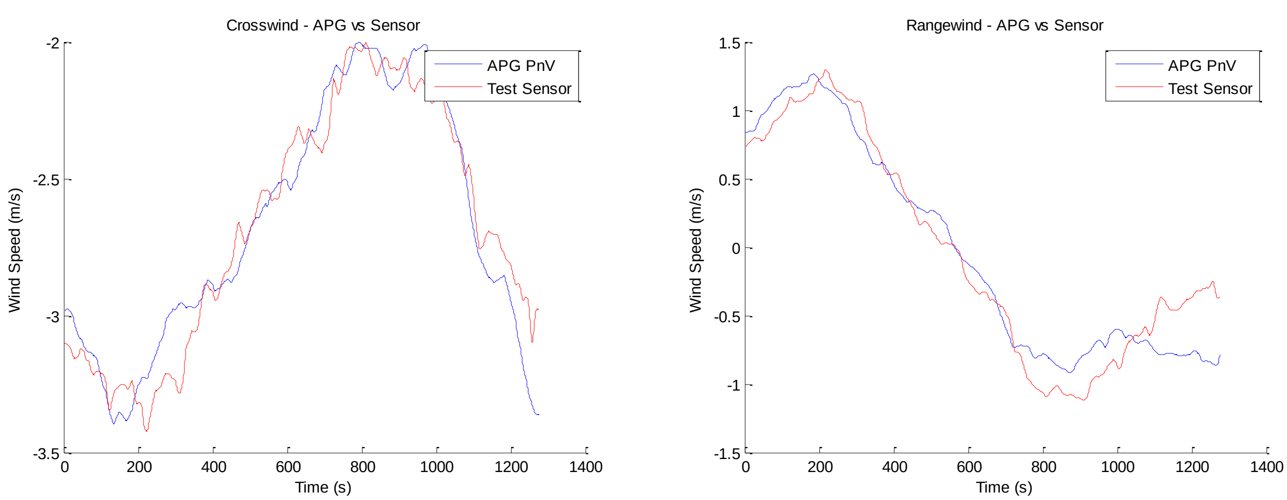

Figure 8: Comparison of the LIDAR Anemometer 10 min Average and PnV Anemometer 10 Minute Average

Figure 8 shows that the two sensors follow the same long term trends and that the difference between the readings is small. The correlation coefficient was 0.96, the mean error was 0 m/s, and the standard deviation of the error was 0.21 m/s. These metrics and figure show that the data between the two sensors is aligned correctly.

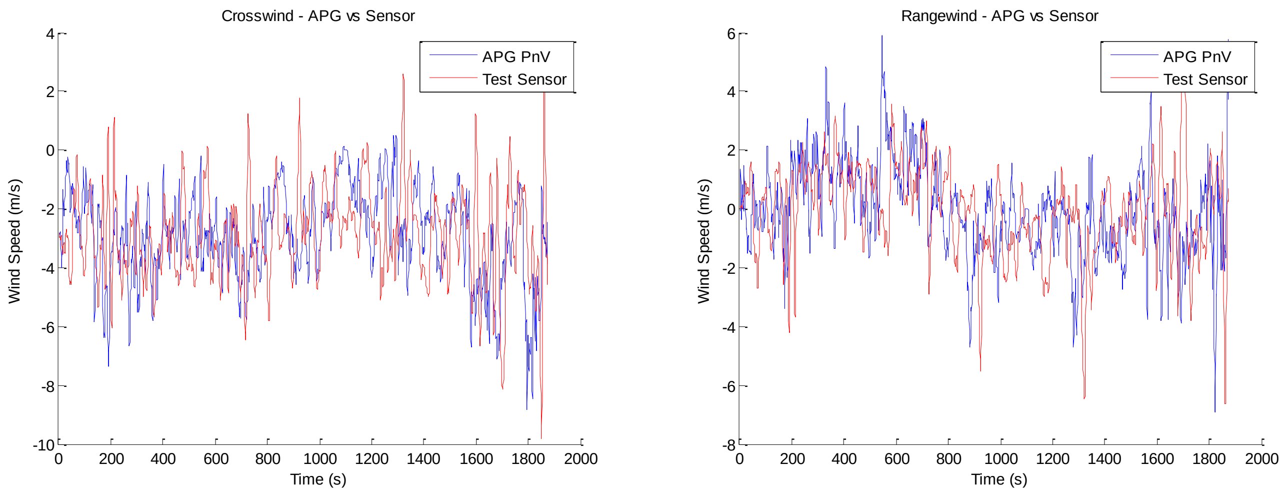

Figure 9: Comparison of the LIDAR Anemometer 1 sec Average and PnV Anemometer 1 sec Average

Figure 9 shows that the instantaneous readings from the sensors are very different. This is verified by a correlation coefficient of 0.02 and a standard deviation of the error of 2.05 m/s. The mean error was 0.

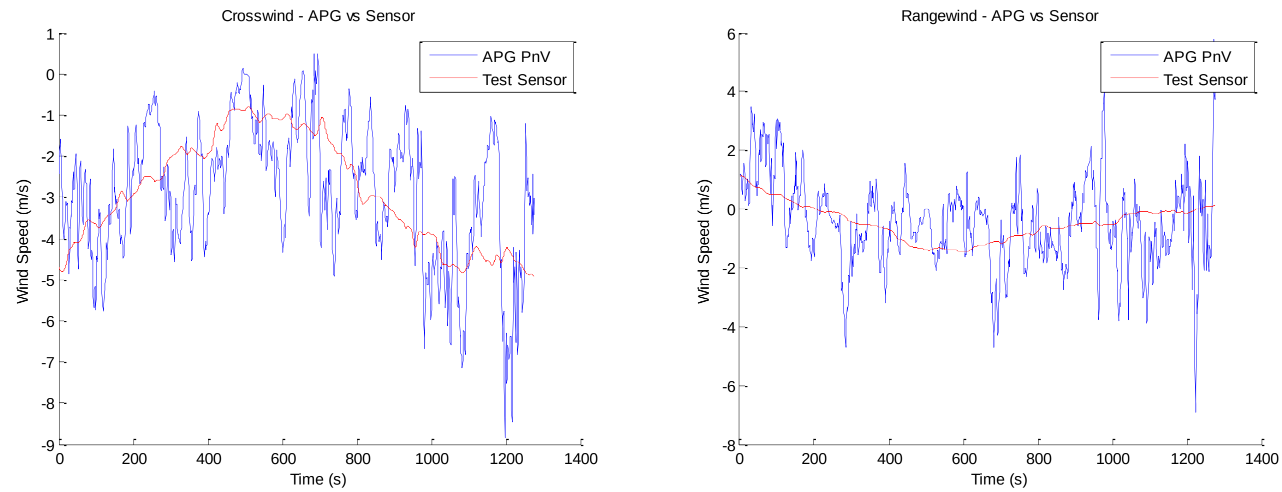

Figure 10: Comparison of the LIDAR Anemometer 10 minute Average and PnV Anemometer 1 sec Average

Figure 10 shows that the 10 minute average captures the mean wind values about which the instant values are scattered. The correlation coefficient was 0.31, the mean was 0 m/s, and the standard deviation was 1.44 m/s.

These results show that the LIDAR anemometer is not well suited for reporting the winds at a point in space. Figure 9 shows that using the instant wind readings from a LIDAR sensor would result in a 1σ error of 2.09 m/s. As a comparison, the current local cross wind sensor being used in modern FCSs has a 1σ error of 1.75 m/s. Figure 10 shows that if the sensor could sample the wind for 10 minutes, it would reduce the 1σ error to 1.44 m/s.

Capturing the Wind

The results presented show that the wind values can be thought of having a long term trend about which they deviate. This can be seen in Figure 7 and Figure 10. The instant wind values in both graphs are centered around a non-zero value that slowly changes with time. If the wind values did not have any long term trends, then the instant values would be centered around a value of 0 for the duration of the data collection. The analysis showed that both sensors captured these long term trends accurately. This was seen in Figure 5 and Figure 8. However, only the HW anemometer was able to capture the short term deviations as seen Figure 6 and Figure 9.

The difference between the results for the two sensors can more than likely be attributed to the difference in the sample spaces used by each sensor. If the wind field moving over a sensor is imaged as a large air mass having an average speed (long term trend) and exhibiting internal variations (short term deviations) then different sample spaces used by the sensors would return different results. The HW anemometer would report the movement of the air mass along with the internal variations within that air mass at a point. The LIDAR would report the movement of the air mass along with the average internal variation of the sample spaced used. This can be visualized as:

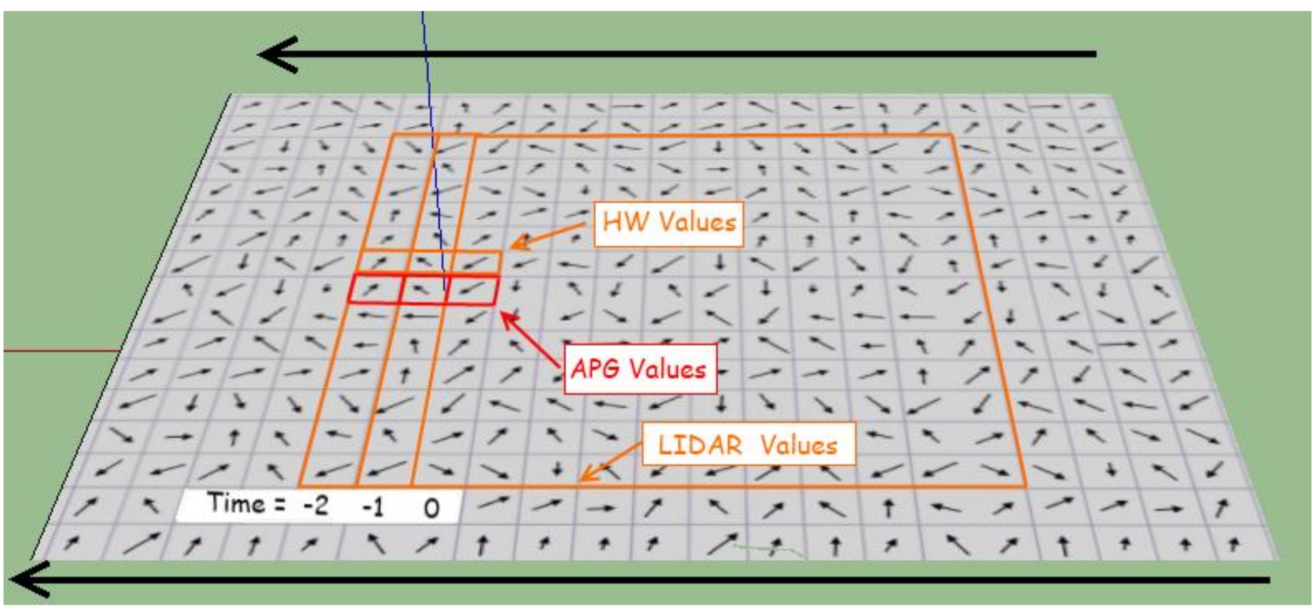

Figure 11: Wind Sampling Methods

Figure 11: Wind Sampling Methods shows that the sample space used by the HW anemometer is much closer to the APG sample space than the LIDAR sample space. From this, the deduction can

be made that if the sample space of the LIDAR could be reduced to the size of each square in the figure, then the system could be used to make a highly accurate wind correction. However, as it stands, the instant values obtained from the large samples space are not representative of the winds a projectile would be subject to at a discrete point in its trajectory.

Conclusions and Recommendations

The analysis showed that both experimental sensors would be beneficial to a fire control system as each could capture some aspect of the wind. The HW anemometer was able to capture the long term trends as well as the short term deviations in the wind at the sensor location. The LIDAR sensor was only able to capture the long term trends in the wind ahead of the sensor. From an implementation perspective, the HW anemometer would be beneficial to any fire control system that does not already have a range and cross wind sensor. However the LIDAR sensor, in its current configuration, would only be suited for integration onto stationary platforms that are able to collect wind readings for a relatively long time before firing.

It is recommended that further work be conducted to study the utility of LIDAR wind sensors in direct fire weapon applications. While the information presented within shows that the LIDAR sensor does not report the same instant wind readings as a point sensor, the measurements it does provide could still potentially improve a fire control solution. Therefore, it is recommended that a study be conducted that quantifies the increase in the accuracy of a weapon system resulting from wind corrections derived from LIDAR data. Additionally, testing additional LIDAR configurations that shrink the sample spaced used to obtain measurements should be conducted. This exercise would be beneficial as the information presented within implies that a smaller sample space would increase the correlation between the winds affecting a projectile and the winds reported by a LIDAR sensor.

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